Progress on Radio Frequency Cavities for Use in Muon Cooling Channels

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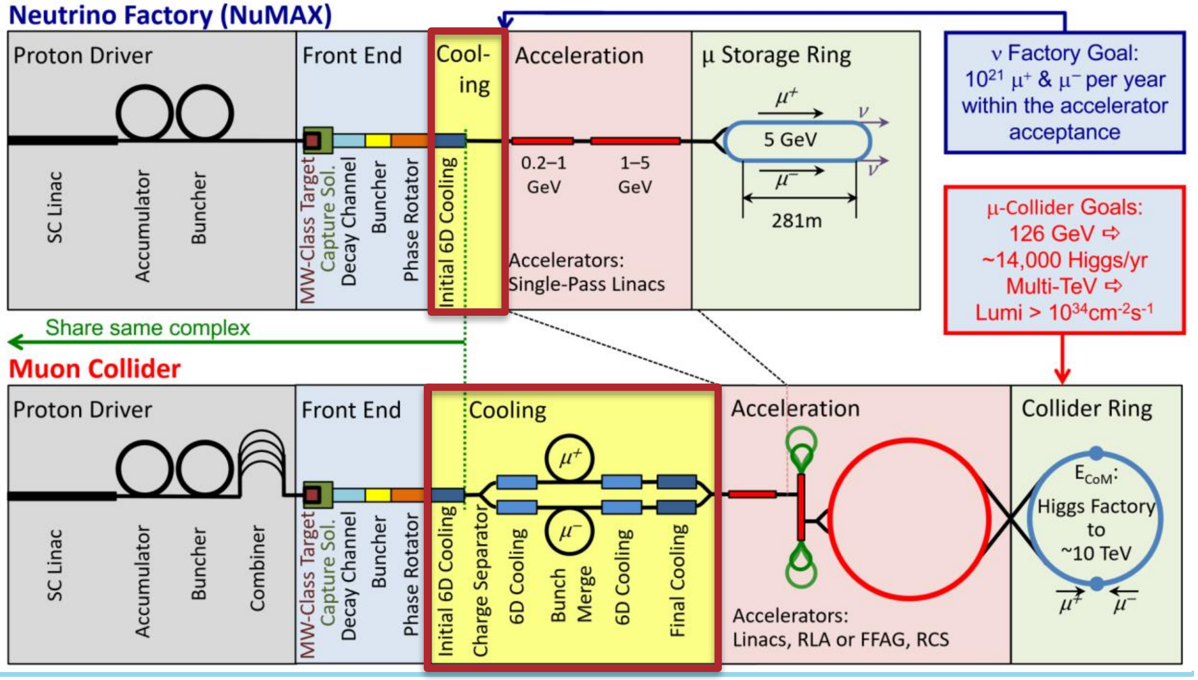
In partnership with:

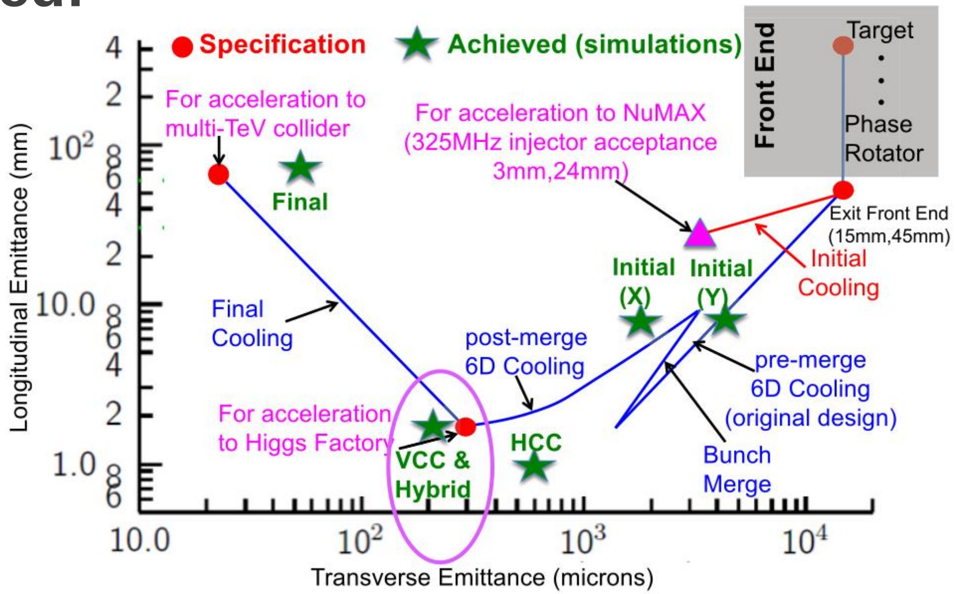
Overview

- US Muon Accelerator Program pursued MW class proton beam and target production scheme for muons
- This requires minimal beam cooling for Neutrino Factory (order 50) and significant cooling for Muon Collider (order 10^6)
- Ionization cooling effective (see MICE results: Nature 578 (2020)) but requires RF cavities to operate in strong magnetic fields
- The US MAP conducted extensive R&D on this topic; two solutions to this challenge will be reviewed here



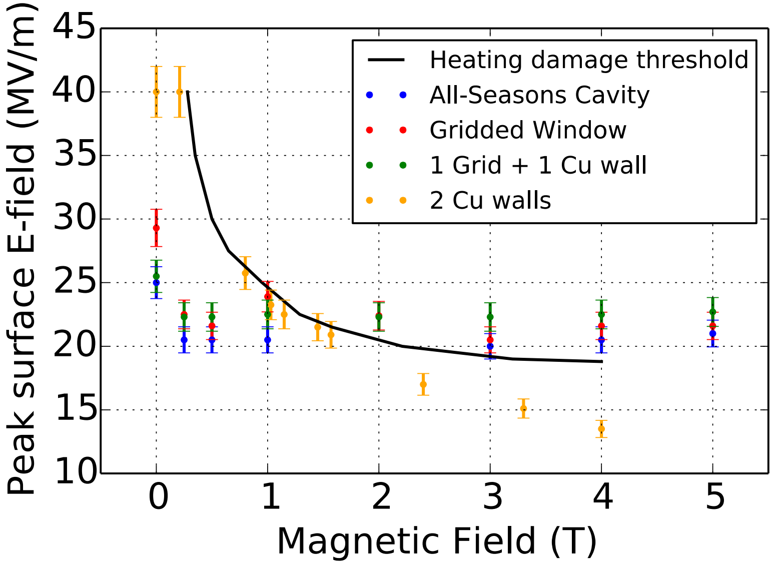
RF Cavities in Muon Cooling Channels

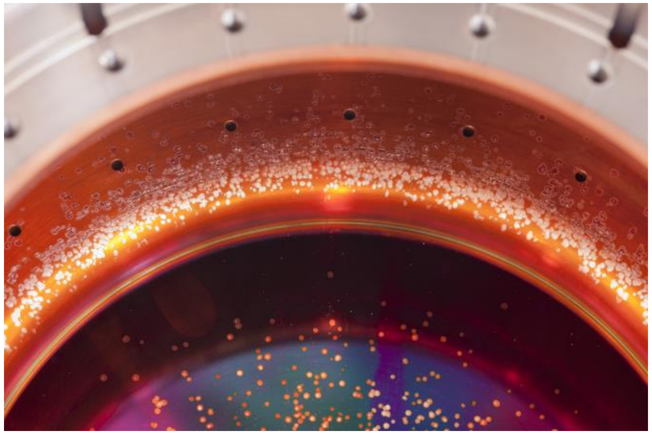
- Early work focused on proof-of-principle: How to operate RF cavities in strong magnetic fields
  - **Two solutions (at least) exist!**
- Later work involved cooling channel design & beam dynamics
  - **Simulations close to or achieve emittance specifications**
  - **Experimentally achieved gradient exceeds simulated; re-optimization needed!**



RF breakdown limits accelerating gradient

- Ionization cooling requires high-power RF structures to operate within multi-tesla B-fields.
- Initial R&D addressed breakdown in magnetic field
- We reproducibly observe a significant degradation in the max. achievable E_{acc} for these structures.



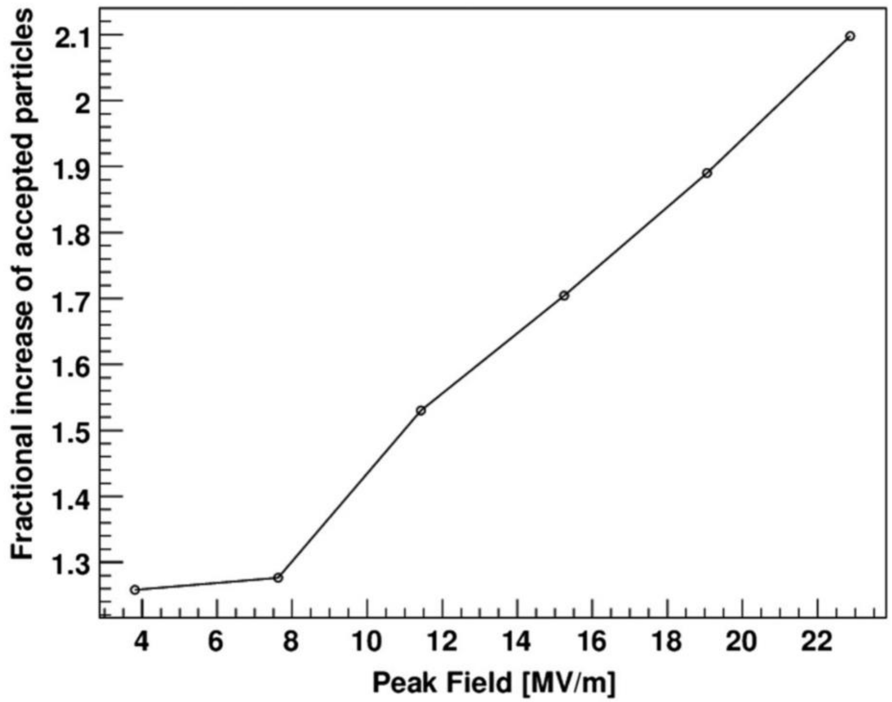


Breakdown damage

D. Bowring et al., Proc. IPAC 2015

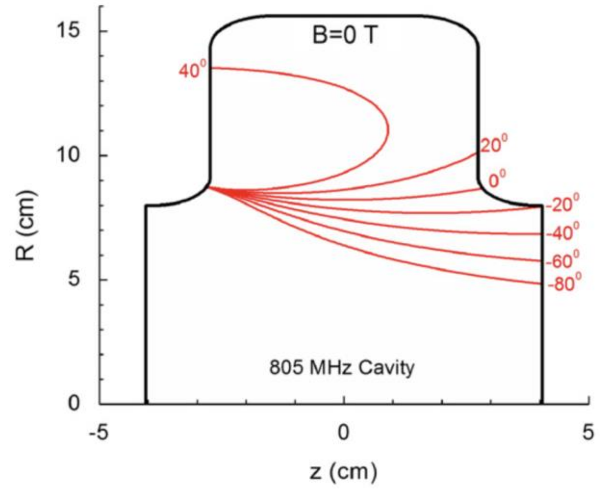
Accelerating gradient limits cooling channel performance

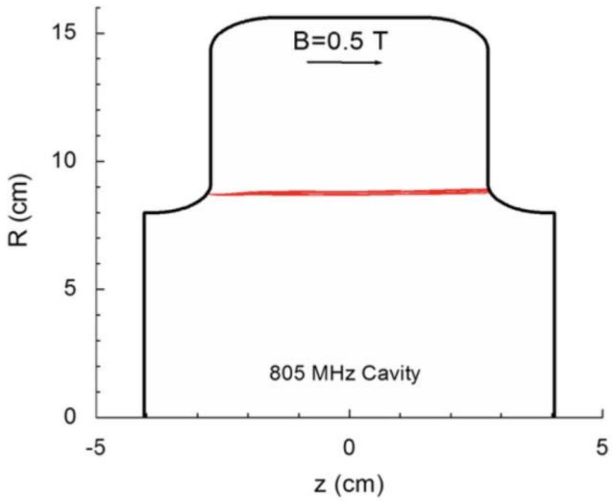
- Low gradient depresses muon yield through channels
  - Longer channel
  - Worse cooling performance
- This is an undesirable constraint on channel designs



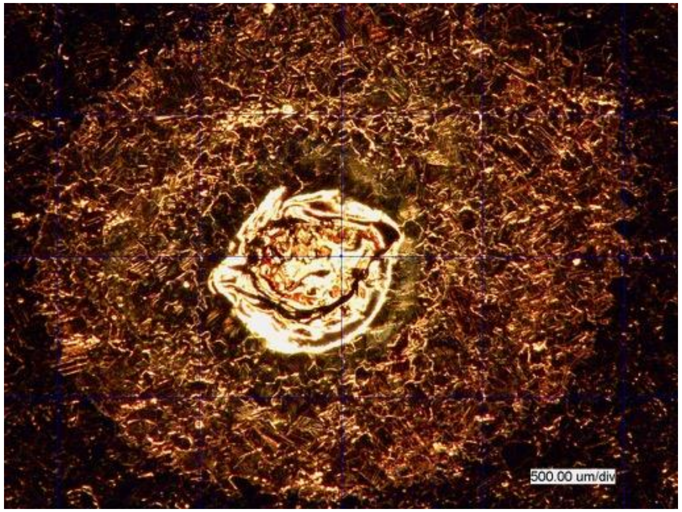
One example: [CT Rogers et al., PRAB 16, 040104 (2013)] simulated linear degradation in performance w.r.t. peak accelerating field.

How can we explain the effect of the *B*-field?



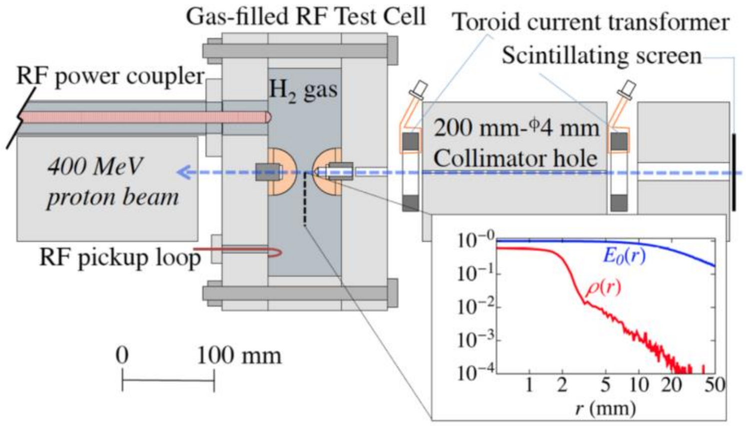


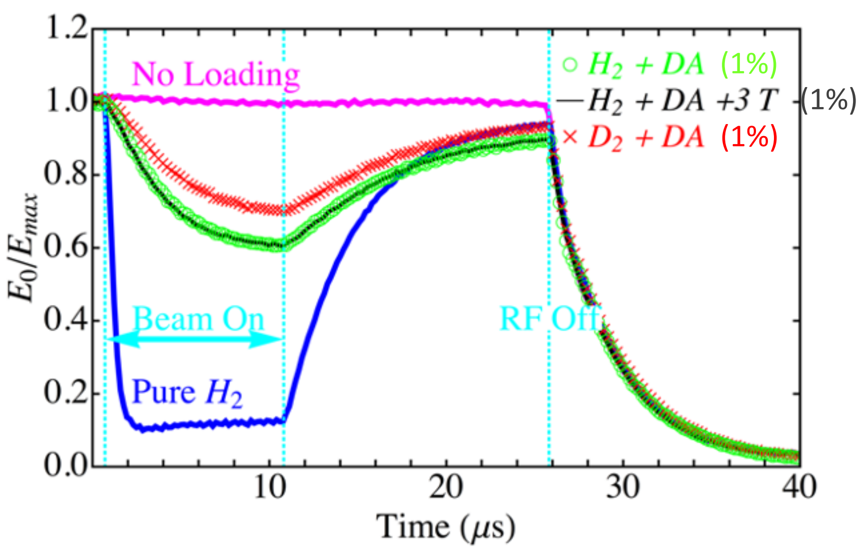
- Field emission sources electrons in cavity volume
- e⁻ trajectory phase dependence varies with *B*-field.
- For *B* > 0, "beamlets" can cause pulsed heating, cyclic fatigue of cavity surfaces.
- D. Stratakis et al. NIMA (2010).



Microscope image of breakdown damage

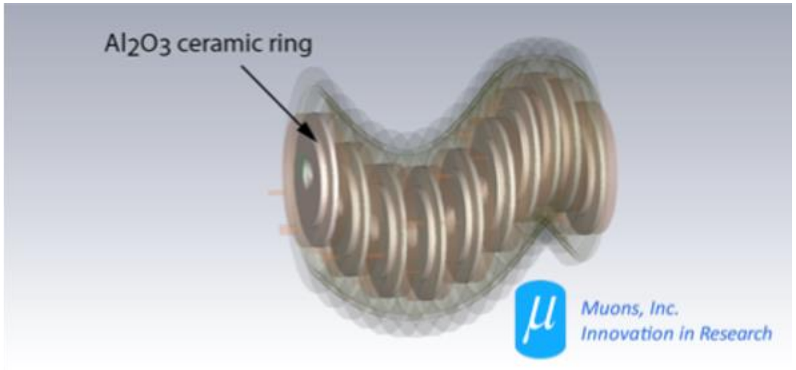
Loading cavities with high-pressure gas circumvents the problem.

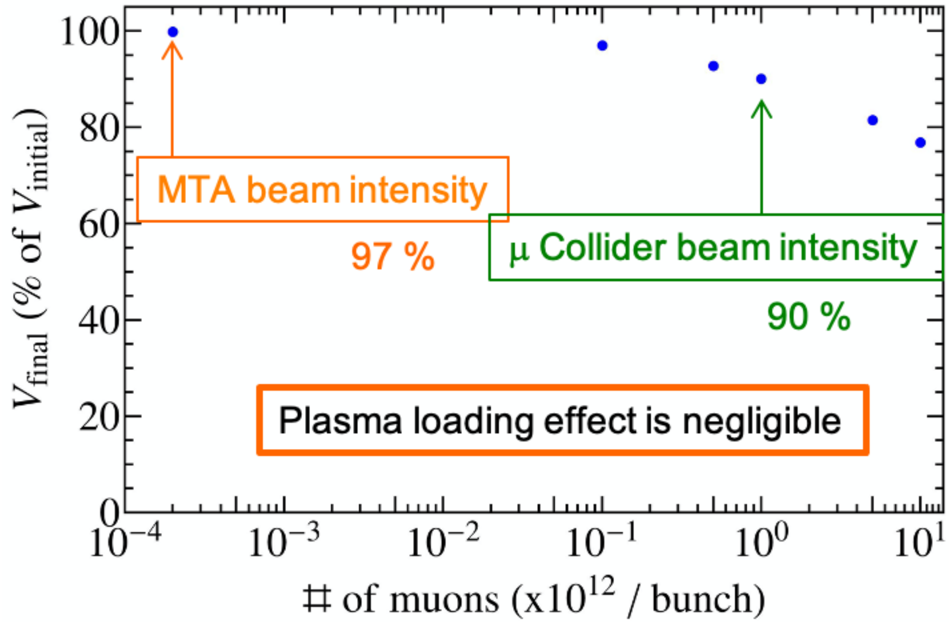




- Gas prevents electrons from causing breakdown *and* serves as cooling medium
- Doping with electronegative gas reduces loading from beam-induced plasma.
- B ≤ 3 T shows no effect on cavity gradient.
- PRL 111, 184802 (2013)
- PRAB 19, 062004 (2016)

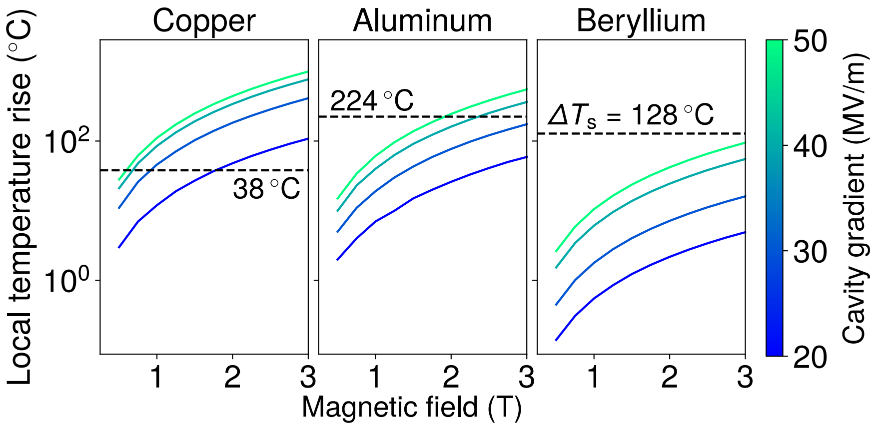
“HPRF” approach has been used in several channel design/simulation efforts.



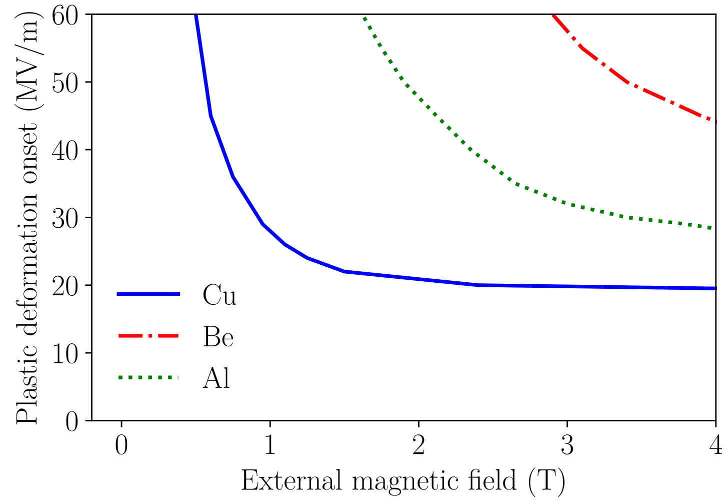


- Helical Cooling Channel (above) K. Yonehara, arxiv:1806.00129
  - Predicted cavity loading due to plasma manageable at Muon Collider bunch intensities
- Rectilinear FOFO: D. Stratakis, arxiv:1709.02331
- Helical FOFO “snake”: Y. Alexahin, MAP-doc-4377

Vacuum cavities with non-traditional wall materials studied

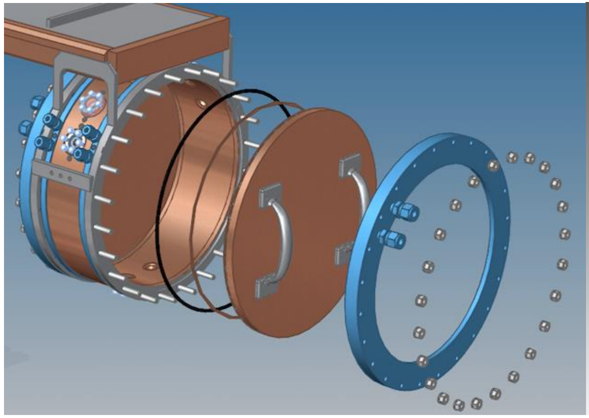


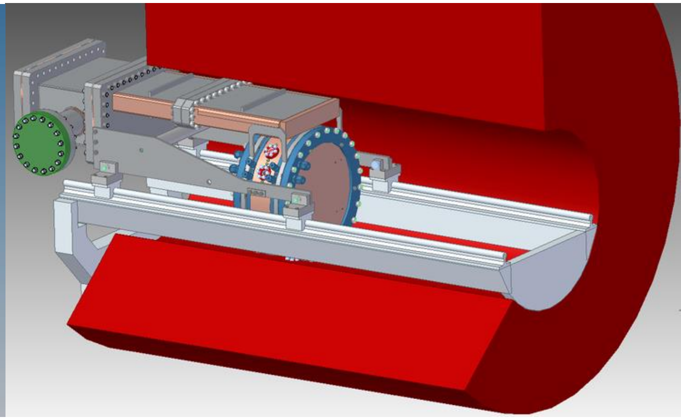
Electron beamlet current density varies with *B*-field. Heat deposition rises above plastic deformation threshold at different points depending on material.



Predicted maximum achievable gradient vs *B* for Cu, Be, and Al.

- Model including material properties directed experimental thrust
- "Modular Cavity" with removable walls tested
- Beryllium performance directly, experimentally compared with Cu.





Fermilab

Beryllium cavity walls also allow for safe operation

Material	B-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07
Be / Cu	0	43.9 ± 0.5	1.18 ± 1.18
Be / Cu	3	10.1 ± 0.1	0.48 ± 0.14

- SOG = "safe operating gradient", at which breakdown probability (BDP) < 10^{-5}
- ~50 MV/m achieved in 3 T field with beryllium walls
- For beryllium case, limiting factor was RF infrastructure *not* cavity breakdown.
- [D. Bowring, PRAB 23, 072001 (2020)]

Summary

- Significant cooling required for proton driven Muon Collider
- **Two RF cavity designs experimentally demonstrated proof-of-principle concept for muon cooling channels**
  - High pressure gas filled & vacuum with beryllium walls
- **Simulated cooling channels meet or are close to emittance specifications for Higgs Factory or multi-TeV collider**
  - see D. Stratakis talk
  - Experimentally achieved gradient exceeds simulated one; re-optimization needed
- With completion of MICE ([Nature 578 (2020)]), prototype RF cavity design and cooling channel next step